Development of a Flex-Fuel Mixing Controlled Combustion System for Gasoline/Ethanol Blends Enabled by Prechamber Ignition

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Project ID: ace184

2022 DOE Vehicle Technologies Annual Merit Review

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BE THE DIFFERENCE.

Overview

Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

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Timeline

- Start: April 2022
- End: July 2025 (39 months)
- ~7% complete

Budget

- Total Funding: $3.125M
  - DOE Funding: $2.5M
  - Cost Share: $625k (20% share)

Partners

John Deere, The University of Wisconsin–Madison, MAHLE Powertrain, ClearFlame Engines, Missouri Corn Merchandising Council

Barriers

- Energy demand for off-road vehicles is growing (agricultural & construction)
- Need to reduce GHG and criteria pollutant emissions is imminent
- Due to high loads, high duty cycles, and long operating periods – full electrification of the powertrain does not appear feasible without sacrificing productivity
- Using clean burning alternative fuels with of low lifecycle GHG emissions – the most pragmatic approach to decarbonize heavy-duty vehicles
- Readily available domestic fuel – bioethanol (E15 → E30 → E85 → E100)
- Heavy-duty engines rely on non-premixed mixing-controlled combustion for its operational characteristics (e.g., snap torque, high torque at low speed, high efficiency, robustness, controllability)
- Premixed spark ignited engines don't deliver these performance characteristics & high-octane gasoline/ethanol blends have very low cetane #
- ***Challenge:*** Desire to use high-octane gasoline/ethanol blends but maintain non-premixed mixing-controlled combustion process

Relevance (1/2)

Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

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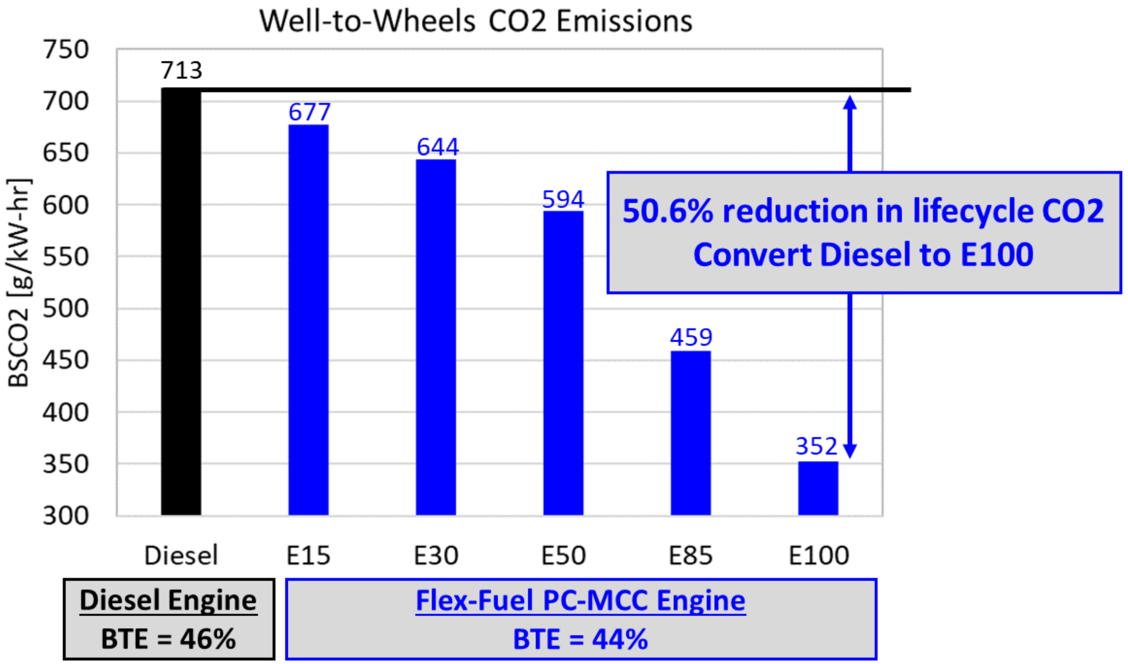
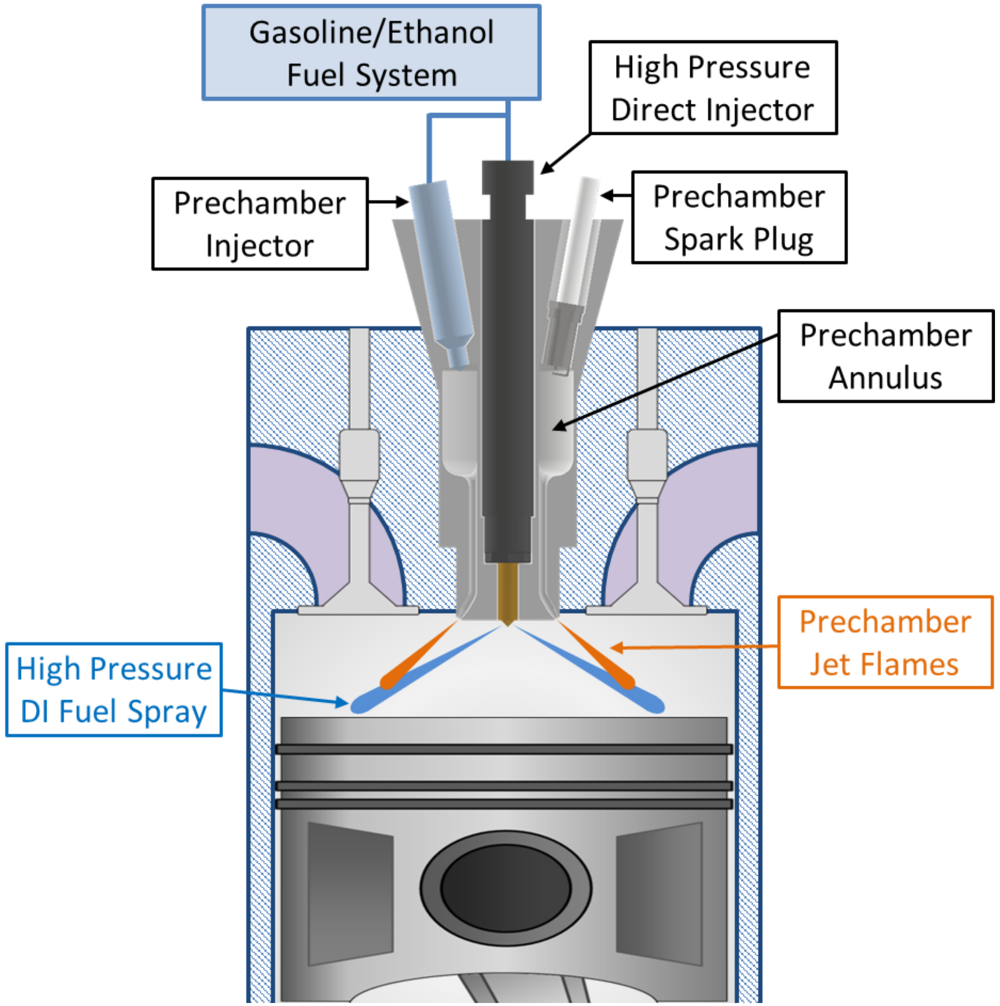
Impact

- Prechamber ignition assistance technology that enables flex-fuel operation (E15 to E100) while maintaining mixing-controlled combustion and diesel-like efficiency and performance characteristics.
- Torque and power output will not be sacrificed and potentially could increase
- Using renewable US corn-based ethanol, ~50% reduction in lifecycle CO_2





Relevance (2/2)

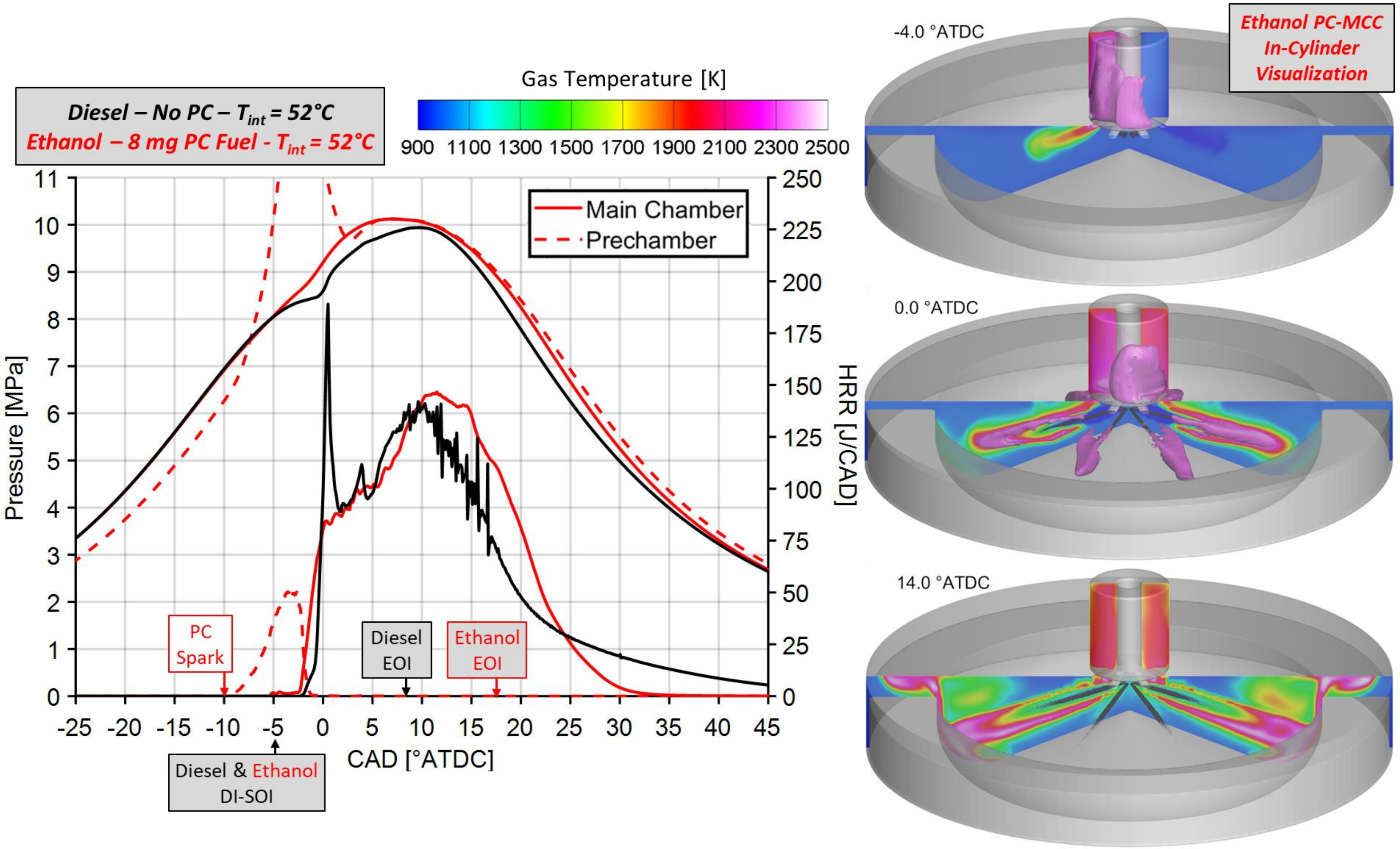
Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

Objectives

- Develop active prechamber ignition system to enable mixing-controlled combustion of any gasoline/ethanol fuel blend over the entire engine operating space.
- Preliminary CFD modeling has demonstrated the concept can reproduce the "diesel combustion" process using E100 without modifying the engine's air handling system.

Full Program Objective

- Objective of the project is to research, develop, and validate a heavy-duty flex-fuel engine capable of a 5% to 50% reduction in life cycle CO_2 emissions compared to diesel when operating on fuels from E15 to E100.
- Ultimate engine technology will retain the torque curve and general operating characteristics of the modern diesel engine.

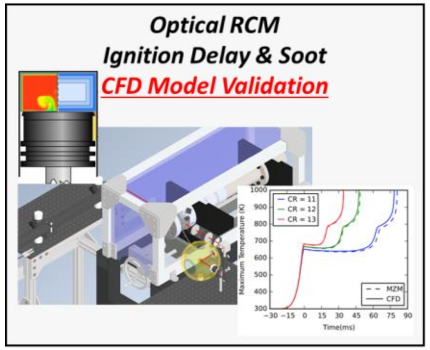


Approach

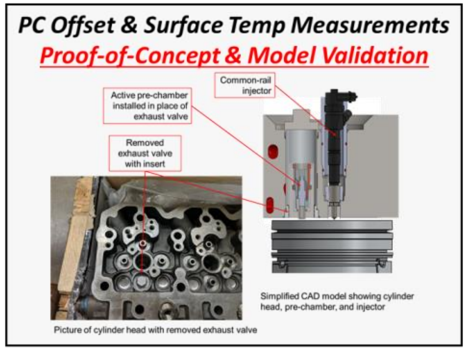
Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

- The project team has vast expertise in experimentation, simulations, design, fabrication, and systems integration.
- **<u>Project Approach:</u>** RCM experiments to develop and validate an engine CFD modeling approach, engine CFD modeling and proof-of-concept experiments, design and fabrication of prototype prechamber igniter, single-cylinder engine experiments, multi-cylinder engine demonstration, and technology assessment via techno-economic analysis.

Task #1



Task #2



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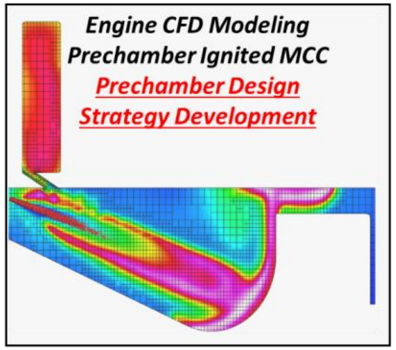

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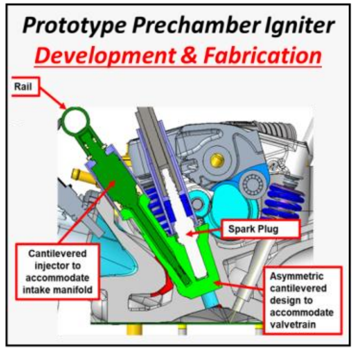
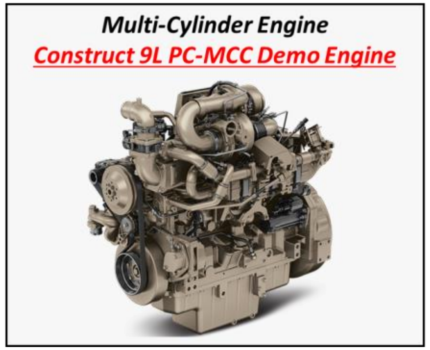


Task #5

Task #6



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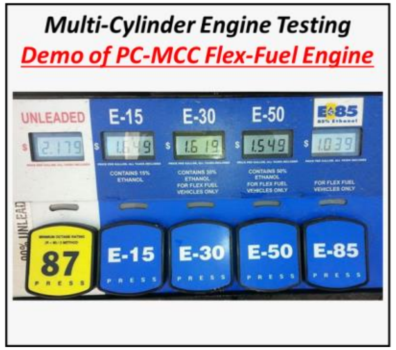

Task #8

Project Milestones

Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

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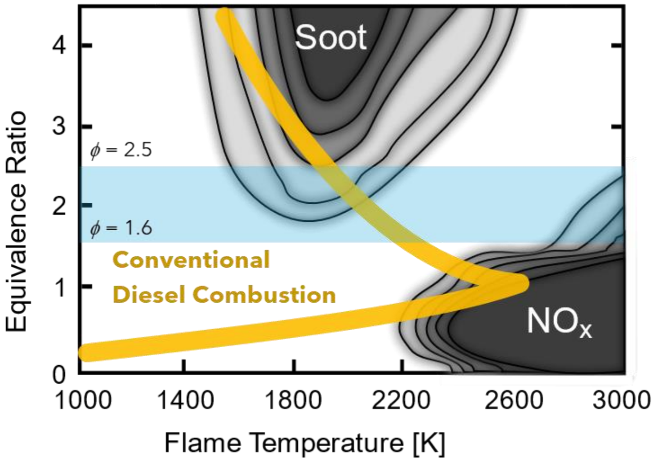
			BP 1					BP 2				BP 3			
Name	***Description***	***Status***	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**
Required Prechamber Volume & Passageway Size	Use CFD modeling to determine minimum required prechamber volume for robust ignition and an acceptable range for passageway size to ensure proper prechamber breathing.	**On-Track**	**M**												
Locations for Active Prechamber Determined	Select a location that meets packaging requirements, while providing a robust ignition source.	**Future**		**M**											
Finalize Design of Active Prechamber Ignition System	The prechamber volume, passageways, fuel injector location, and spark plug location will be finalized based on CFD modeling. Designed in such a way to maximize mixing, achieve an ignitable mixture at the spark plug.	**Future**			**M**										
CFD Modeling of RCM Experiments	RCM CFD modeling to select a mechanism, fuel surrogate composition, and soot model that most accurately captures the ignition delay and soot formation of the varying gasoline/ethanol fuel blends.	**On-Track**				**M**									
CFD Modeling Demonstration of Prechamber Ignition Robustness for PC-MCC	CFD modeling of the C9.3B single-cylinder engine will demonstrate that the ignition delay of direct injected E10 to E100 is within 3 CAD of diesel fuel with the same engine boundary conditions.	**Future**					**G/NG**								
CFD Modeling Assessment of Need for Fuel Composition Sensor	Determine, based on CFD modeling, if the prechamber fueling strategy can be an open loop controller or if a closed loop controller based on fuel composition is required.	**Future**						**M**							
Initial Validation of Flex-Fuel PC-MCC Concept on Single-Cylinder	Validate initial PC-MCC engine experiments with the operating strategy developed from CFD modeling.	**Future**							**M**						
Fatigue Analysis of the Cylinder Head with Prechamber	Finite element stress and fatigue analysis of the modified cylinder head to assess the high and low cycle fatigue durability of the cylinder head modified to accept the prechamber operating on PC-MCC mode.	**Future**								**M**					
Assessment of Engine CFD Modeling Accuracy	The combustion heat release rate, indicated work, and criteria emissions will be compared between the engine experiments and engine the CFD model.	**Future**									**M**				
Validation of Flex-Fuel PC-MCC with E15 and E100 on a single-cylinder engine	The engine will be validated on E15 and E100 and achieve a coefficient of variation (COV) in indicated mean effective pressure (IMEP) of <5% and indicated efficiency within 2% of the diesel engine data or higher with equal engine-out NOx.	**Future**									**G/NG**				
Conduct Initial Characterization of PC-MCC Concept on Multi-Cylinder Engine	Characterization and mapping will take place to establish performance and emissions of the prechamber ignition concept operated on gasoline/ethanol blends.	**Future**										**M**			
Development of Finalized Operating Strategy for PC-MCC	The model will be used iteratively with the single- and multi-cylinder experiments to develop finalized operating strategies across the entire speed/load range of the engine.	**Future**											**M**		
Total Cost of Ownership (TCO) Assessment of Flex-Fuel PC-MCC Engine in Off-Road Application	A technology assessment based on the validation data of the flex-fuel prechamber ignited MCC concept will be conducted. Comparisons will be made between the current diesel engine technology and the flex-fuel prechamber MCC engine technology to identify the fluid (fuel and DEF) and emissions control cost reduction payback period.	**Future**												**M**	
Comparison of PC-MCC Multi-Cylinder Experiments with Base Diesel Engine & Other Approaches for MCC with Low Cetane Fuels	The performance and emissions data from PC-MCC will be evaluated. Data will also be compared to the diesel baseline data. The comparison will focus on how the technologies can be building blocks for optimizing MCC with low cetane fuels.	**Future**													**M**

Technical Accomplishments & Progress (1/2)

Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

Optical RCM Ignition Delay & Soot Formation Measurements

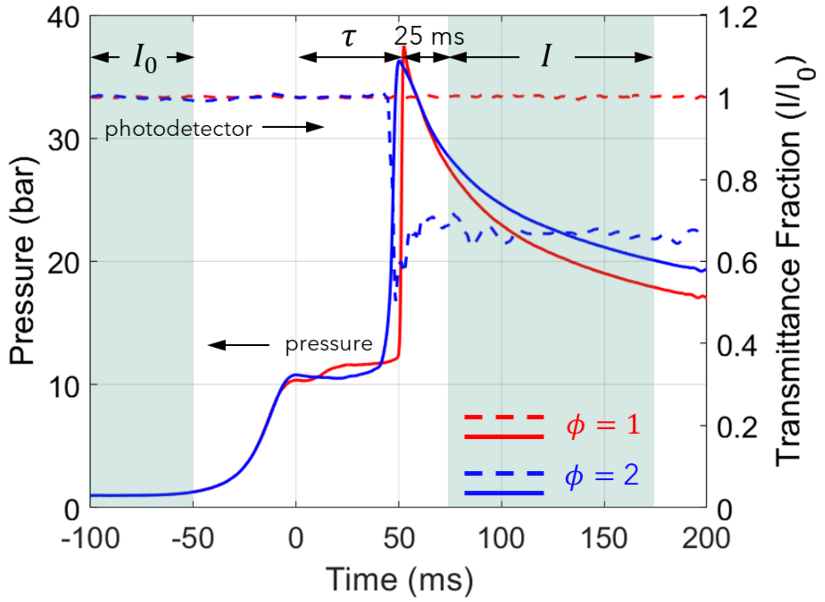
- Experimental study the ***ignition delay*** and ***soot formation*** of gasoline/ethanol fuel blends under fuel-rich conditions → Mixing-Controlled Combustion
- To Date: Characterized iso-octane & ethanol
- Current Project: Study gasoline BOBs with ethanol (E10 to E100)
- Data to select fuel surrogate, chemical kinetic mechanism, and soot model settings to accurately predict combustion and emissions of PC-MCC engine using CFD modeling

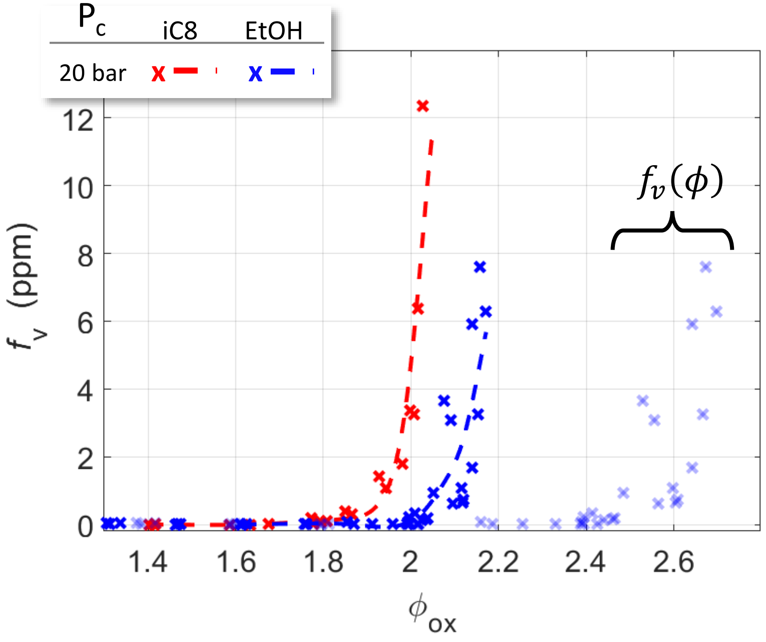


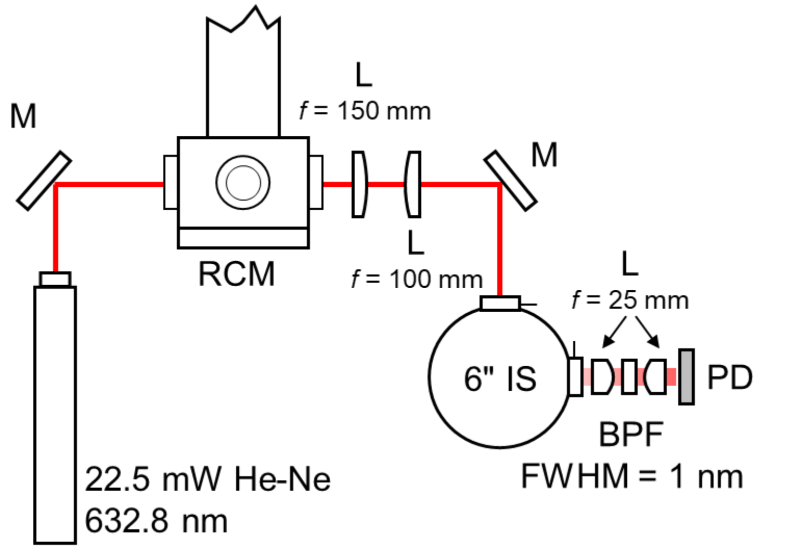
n-heptane soot island
How does it change with gasoline/ethanol fuel blends?

$$\phi = \frac{AFR|_{stoich}}{AFR|_{actual}}$$

$$\phi_{ox} = \frac{2\sum_i X_i C_{\#,i} + \frac{1}{2}\sum_i X_i H_{\#,i}}{\sum_i X_i O_{\#,i}}$$





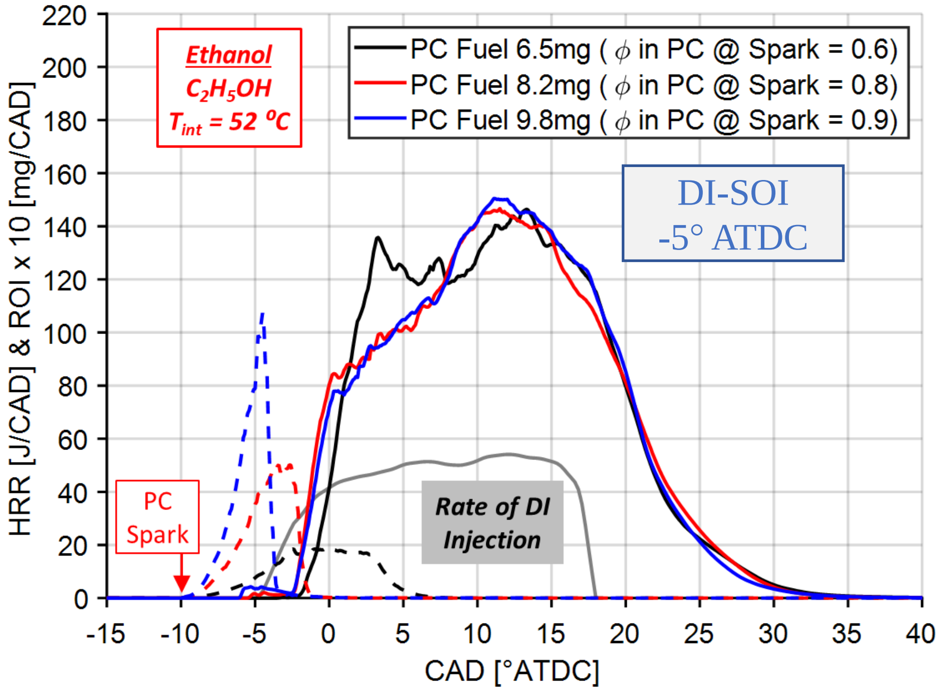


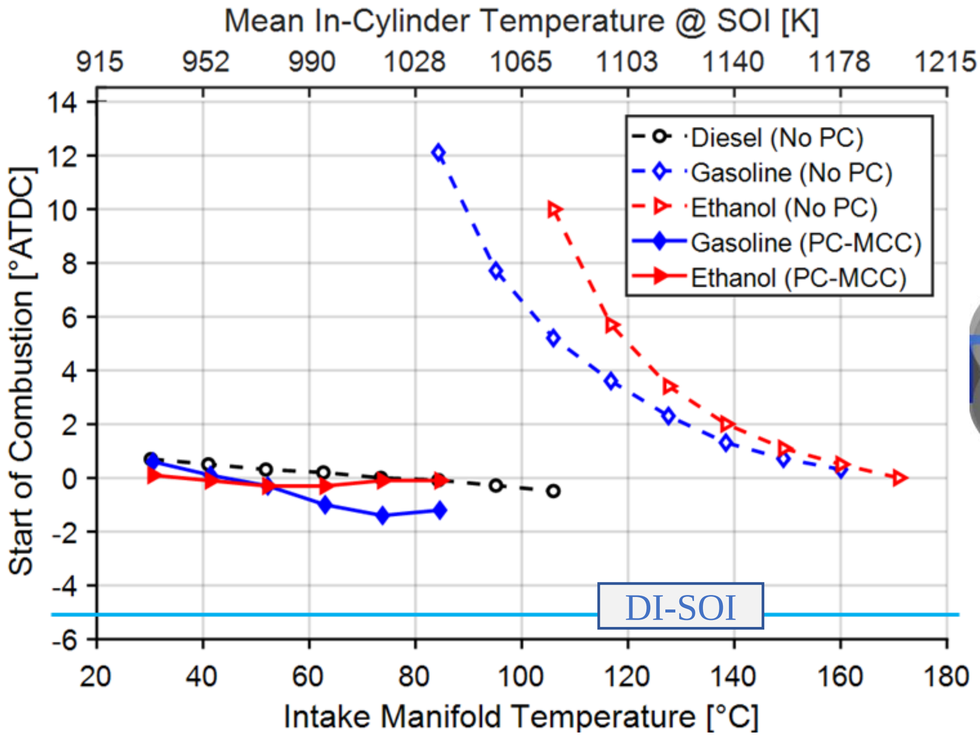
Technical Accomplishments & Progress (2/2)

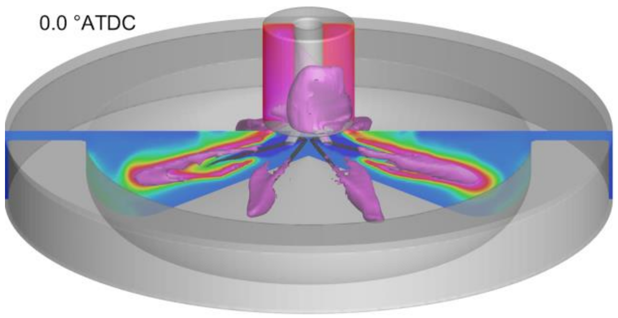
Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

CFD Modeling of PC-MCC Concept – Robust & Fuel-Flexible Combustion System

- CFD modeling of a 1.6L single-cylinder engine (9.3L in-line six) using Prechamber Ignited Mixing-Controlled Combustion (PC-MCC)
- Same ignition delay as diesel when operating on iso-octane or ethanol, regardless of the intake conditions → **Robust & Fuel-Flexible**
- Main chamber combustion process **unaffected** by prechamber heat release rate, which may vary from cycle-to-cycle







Collaboration & Coordination with Other Institutions

Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

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Program Lead
PC-MCC Combustion System Development via CFD Modeling & Single-Cylinder Engine Experiments

MAHLE Powertrain

Prototype Prechamber Design & Fabrication
Cylinder Head Design & Fatigue Analysis

JOHN DEERE

Construction of Multi-Cylinder Demo Engine
Techno-Economic Analysis & Product Feasibility

THE UNIVERSITY of WISCONSIN MADISON

Proof-of-Concept Single-Cylinder Engine Tests
Surface Temperature Measurements in Prechamber

Missouri Corn Merchandising Council

Project Stakeholder & Funding Contributor

ClearFlame ENGINES

Multi-Cylinder PC-MCC Engine Testing
Comparison & Building Block Assessment of CFE Technology

Proposed Research Plan

BP1: Ends July 2023

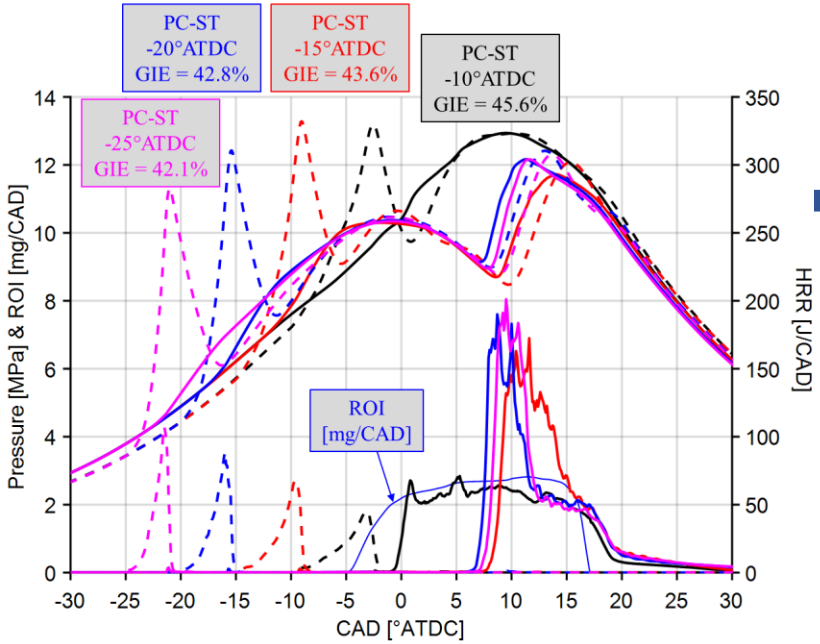
- Develop design requirements for prechamber igniter (PC Volume, Passageway Size, PC-FI & PC-Spark Orientation
- Determine arrangement of PC igniter & DI injector
- Develop PC-MCC Operating Strategy
- Design and Fabricate Prechamber for Single-Cylinder Testing
- Thermal/mechanical analysis
- Proof-of-Concept Experiments with PC in Removed Exhaust Valve

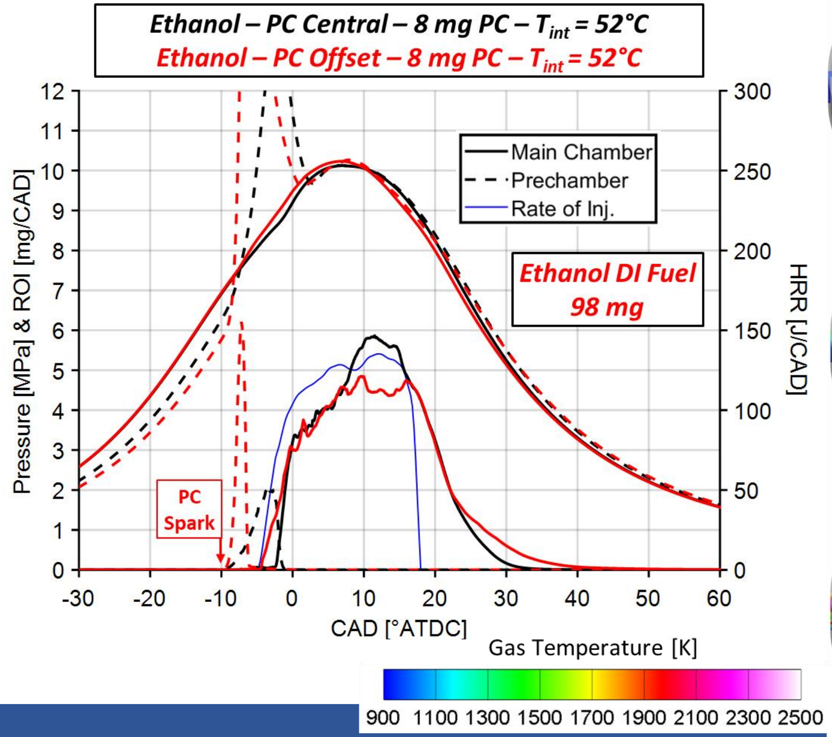
BP2: Ends July 2024

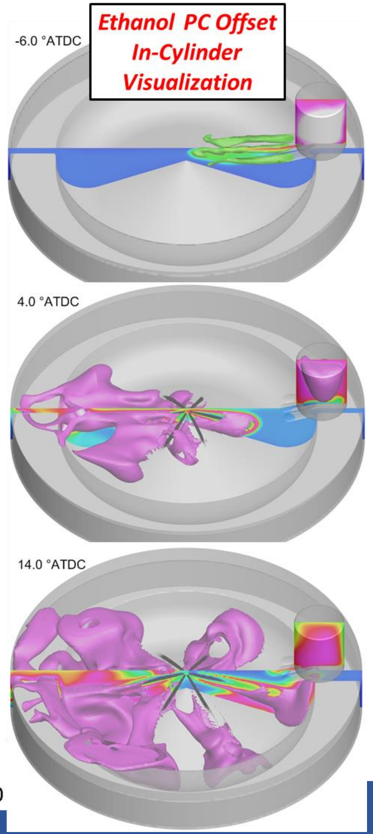
- Single-Cylinder Engine Experiments over entire operating space (E10 to E100)
- Optimize performance & assess accuracy of CFD modeling
- Construction of Multi-Cylinder Demo Engine (John Deere 9L)

BP3: Ends July 2025

- Prechamber surface temperature measurements
- Multi-cylinder engine experiments & demonstration of PC-MCC
- Comparison of PC-MCC to ClearFlame Engine Technology
- Assess building blocks to optimize alcohol MCC operation for HD engines
- Techno-economic & first adopter analysis







Summary Slide

Flex-Fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

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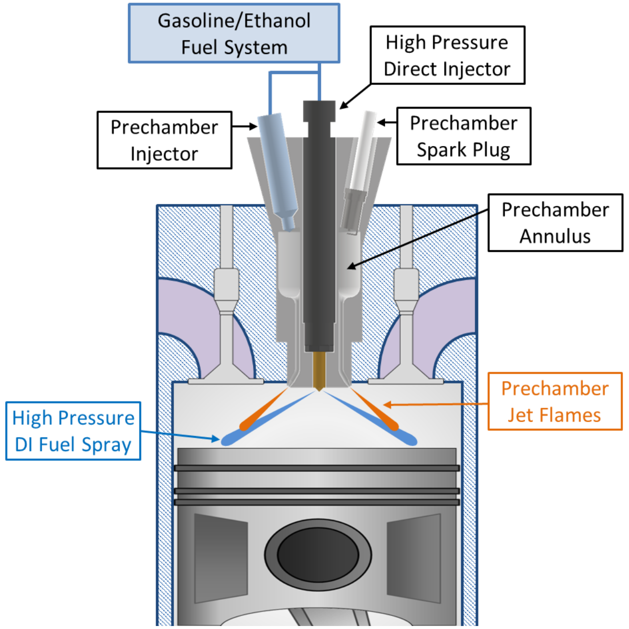
Proposed Objectives:

- Develop a flex-fuel mixing-controlled combustion (MCC) system to use of ultra-low cetane fuels.
- Diesel engine performance characteristics maintained – snap torque, load acceptance, & high efficiency.
- Demonstrate the prechamber ignited MCC strategy on both single- and multi-cylinder engines using gasoline/ethanol blends (E10 to E100). 1) Cover the entire operating space of the base engine, 2) achieve the same level of combustion robustness as diesel combustion (e.g., insensitivity to boundary conditions, prechamber fueling, & prechamber combustion timing), and 3) achieve fuel agnostic behavior.

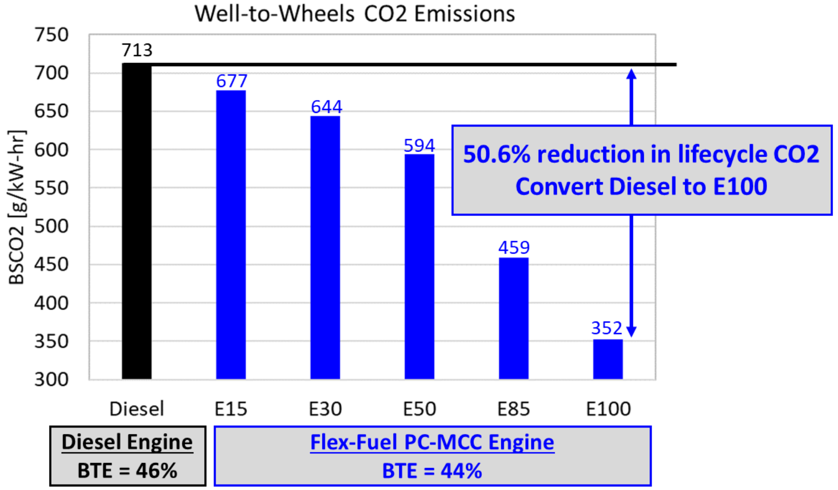


Project Impact/Takeaway:

- Ability to achieve conventional MCC with ultra-low cetane fuels. Diesel engine operating characteristics, meeting heavy-duty customer requirements and allowing for adoption in marketplace.
- Life cycle CO2 emissions reductions can be in the near term. E10, E15, and E85 are available. Higher ethanol blends will yield even higher life cycle CO2 reductions into the future.

Key Deliverables/Accomplishments:

- 10% to 50% reduction in life cycle CO2 emissions compared to diesel when operating on E15 and E100, respectively.
- Reduced total cost of ownership compared to diesel, while maintaining diesel engine operating characteristics.

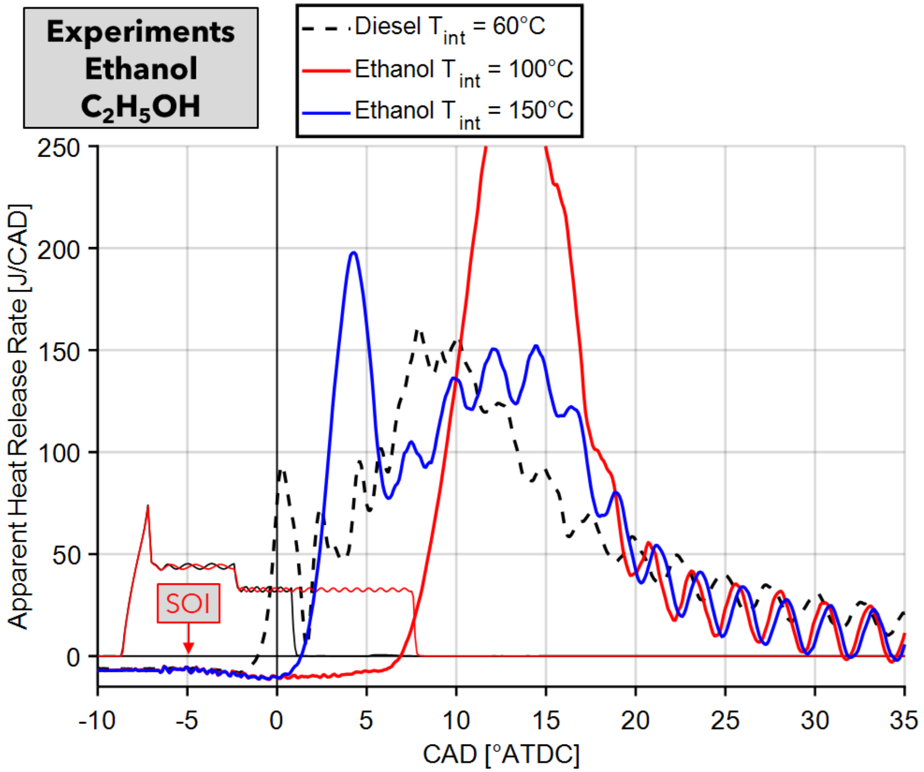


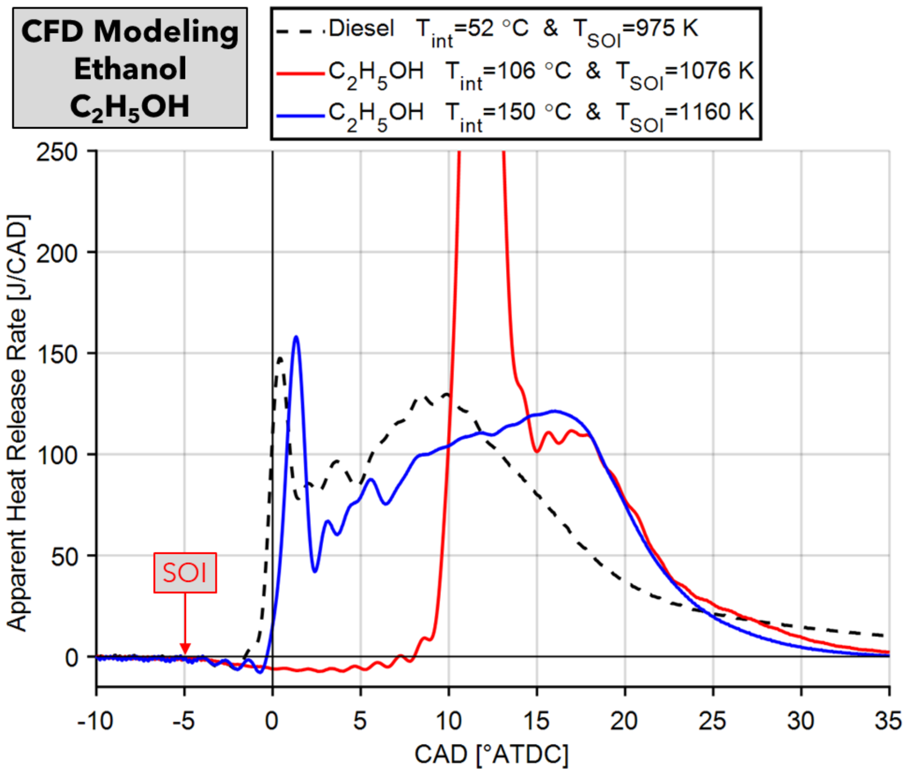
Technical Backup Slides

Project ID: ace184

CFD Modeling & Experiments – Demonstrating MCC with Low Cetane Fuels

No Prechamber Ignition Assistance





CAT C9.3B Engine	
Bore [mm]	115
Stroke [mm]	149
Comp. Ratio (CR)	17
Direct Injector	
# of Noz. & Dia. [mm]	6 / 0.200
Umbrella Angle [°]	145°
Simulated Condition	
Speed [rpm]	1800
Load (IMEPg) [bar]	~ 9.0
Intake Press. [bar-a]	1.75
Intake Temp. [C]	Vary
DI Start of Inj. [°ATDC]	-5.0
AFR & Equiv. Ratio, Φ	
Diesel Fuel	DI Fuel = 60 mg/cyc AFR = 46 Φ = ~0.4
Ethanol	DI Fuel = 98 mg/cyc AFR = 25 Φ = ~0.4

Proof-of-Concept CFD Simulations of Prechamber Ignited MCC
Heavy-Duty CAT C9.3B Engine

Central Annular Prechamber	
Annulus Width [mm]	5
Annulus Height [mm]	20
Prechamber Vol. [cc]	4.3
Prechamber % TDC Vol.	4.2%
# Passageways	6
Passageway Dia. [mm]	2.15
Passageway Angle [°]	120°

Closed-Cycle Simulations (IVC-to-EVO)

- PC fuel assumed premixed at IVC
- Air pushed into the PC during compression stroke
- Single spark plug initiates a propagating flame in PC
- PC Passageway directly above each DI nozzle
- PC jet flames and DI sprays converging

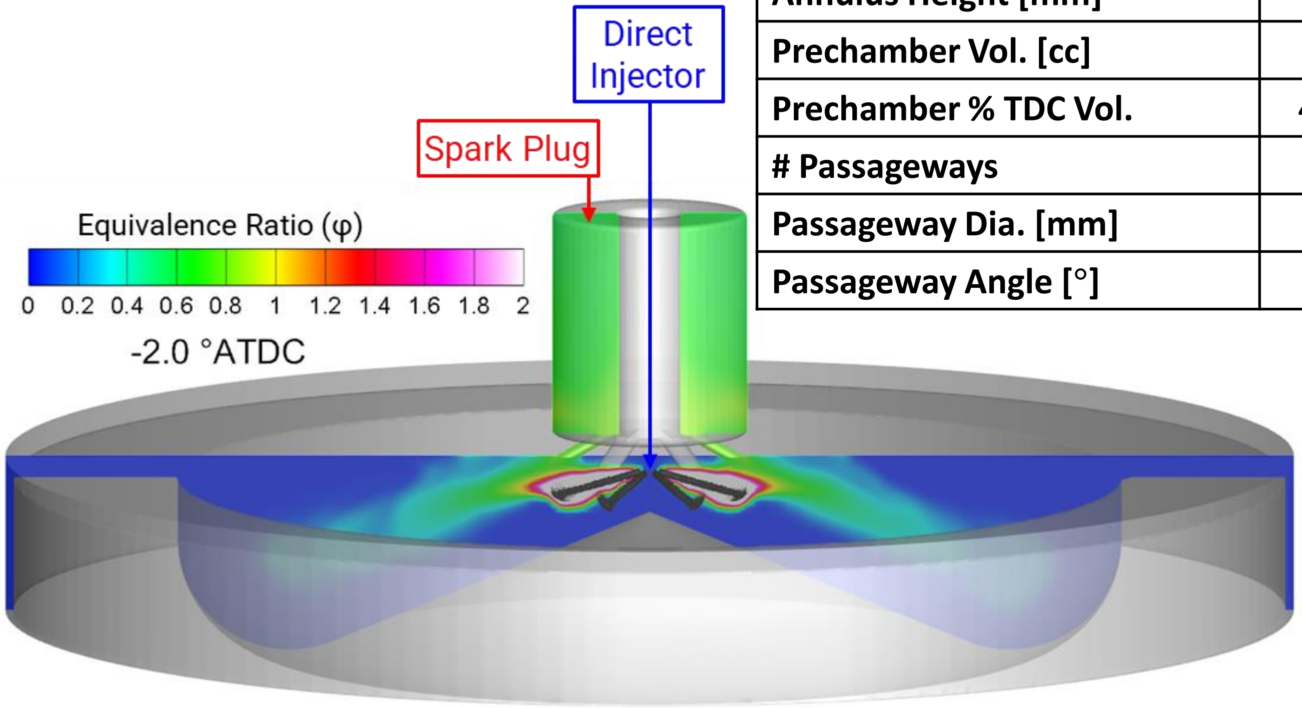
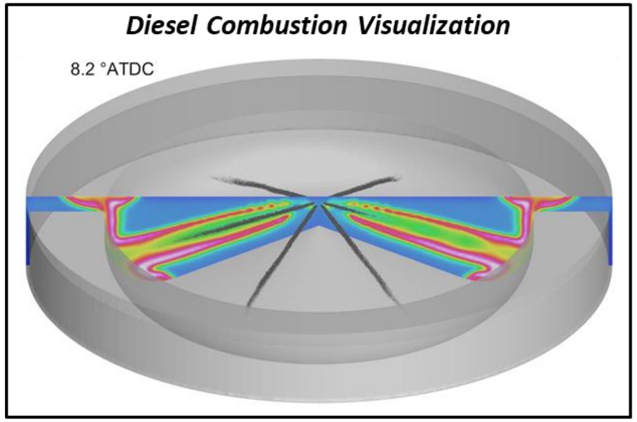
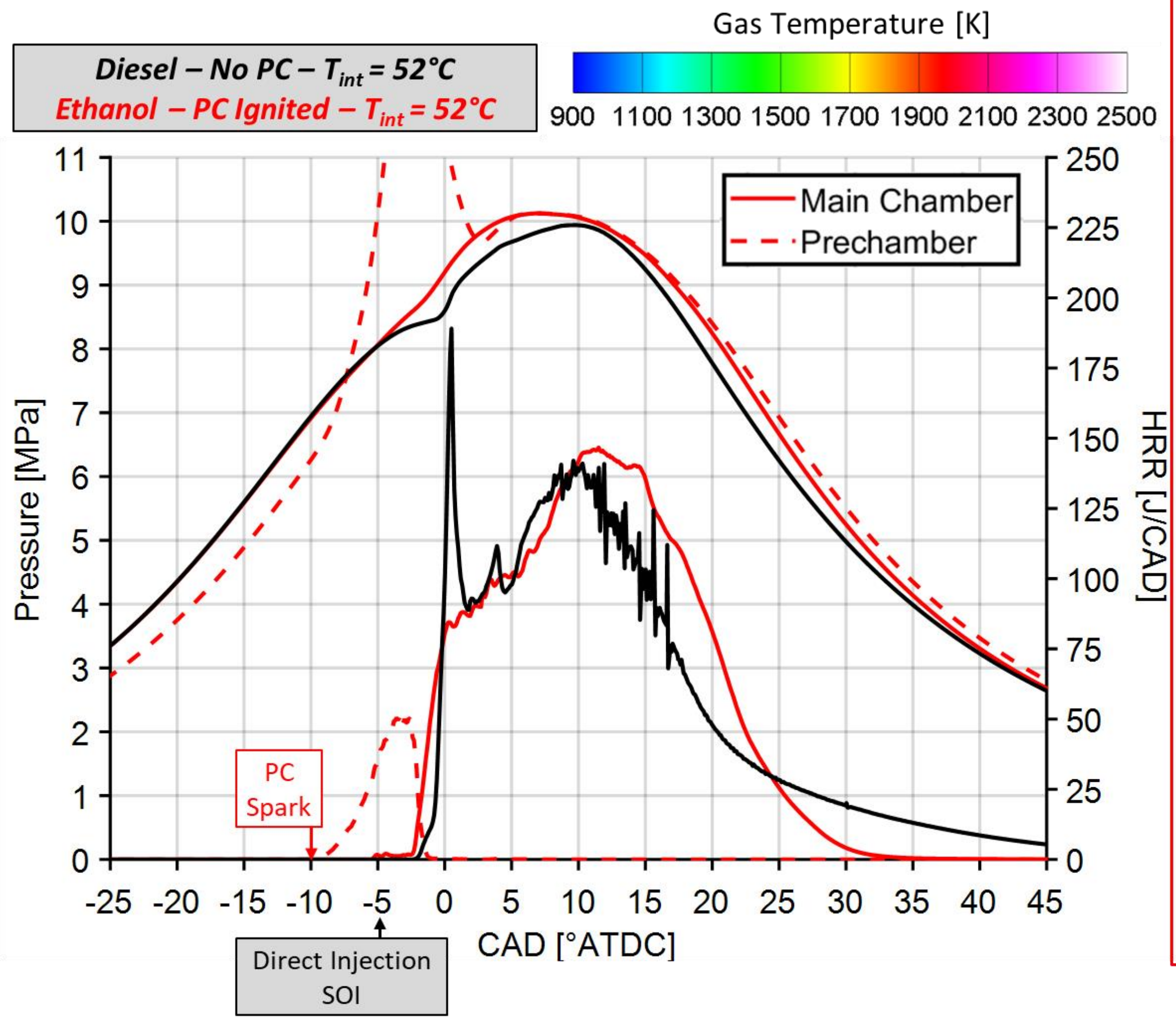
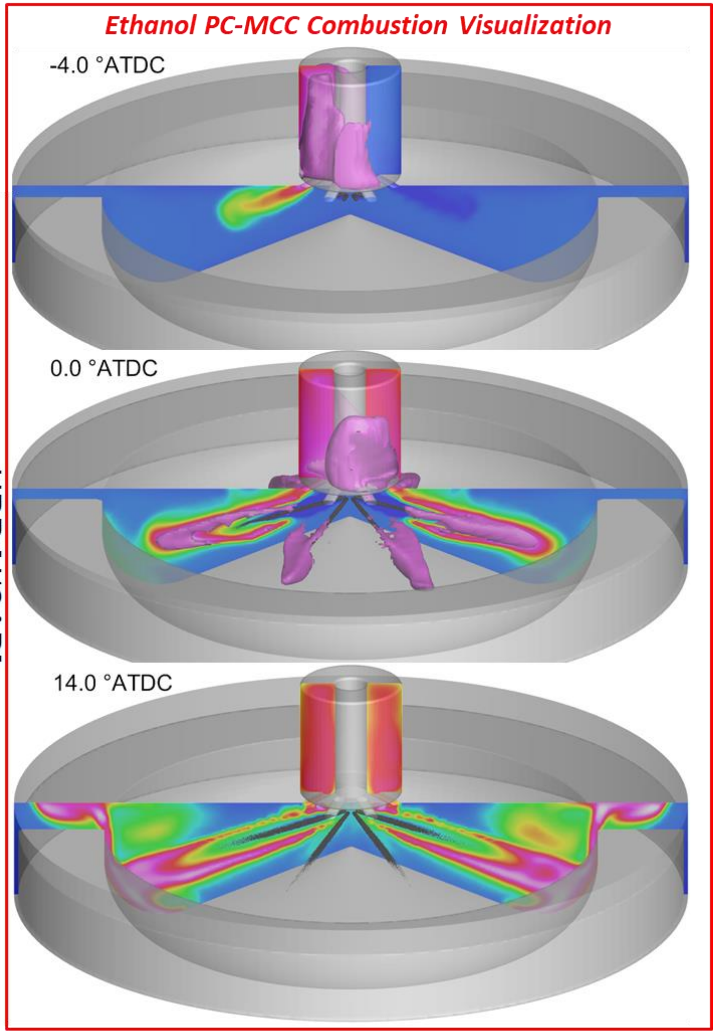


***Image Shown Near DI SOI & ~10 CAD After Prechamber Fired**

Prechamber Enabled Mixing Controlled Combustion (MCC) with Ethanol
Comparison to Conventional Diesel Combustion







	Diesel MCC	*Ethanol PC-MCC*
GIE	50.0%	49.6%
ISNOx [g/kW-hr]	3.6	2.2
ISSoot [g/kW-hr]	0.23	0.04
Comb Eff	99.8%	99.9%

CFD Demonstration of the Combustion Robustness of PC-MCC
Sensitivity to Intake Manifold Temperature

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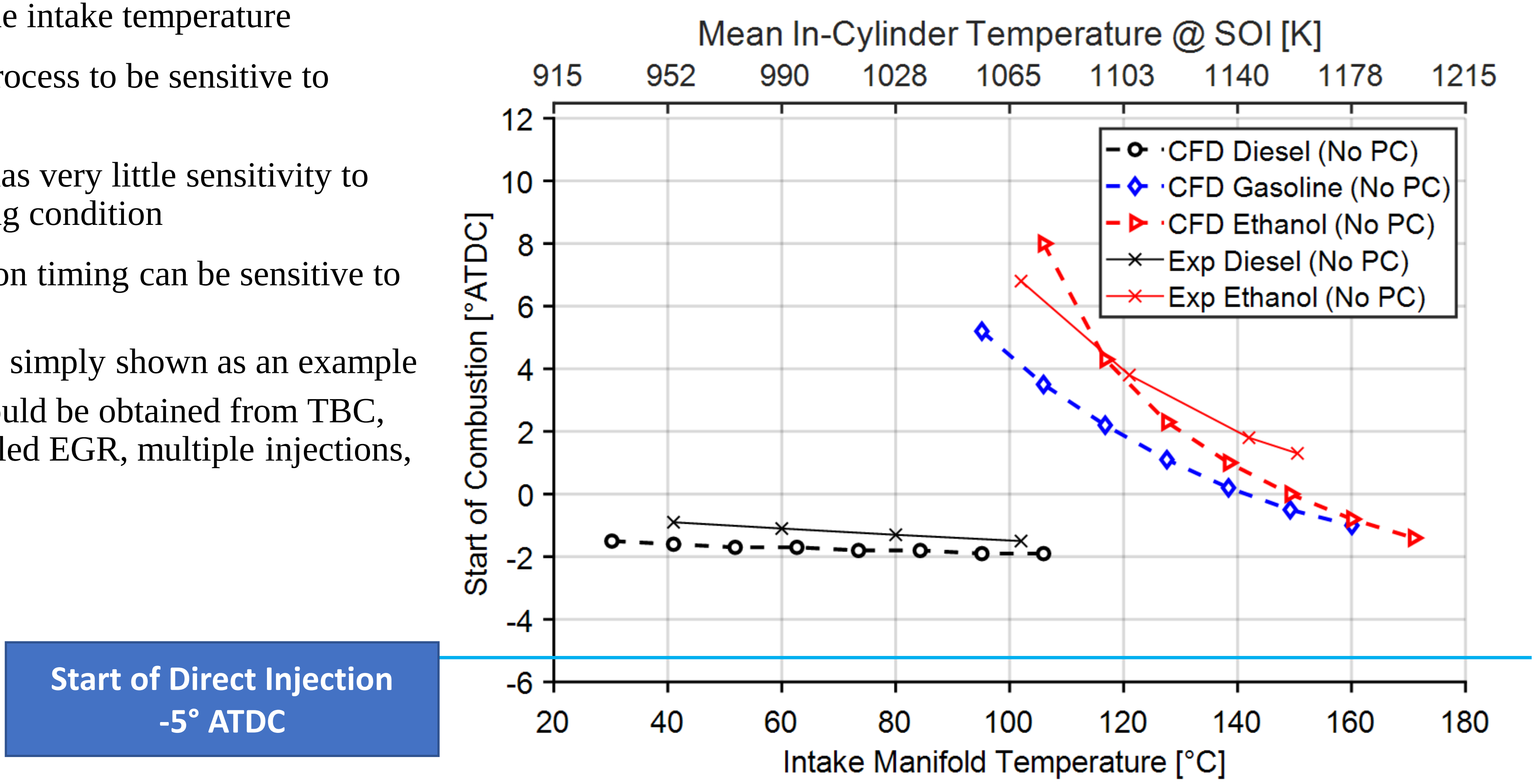
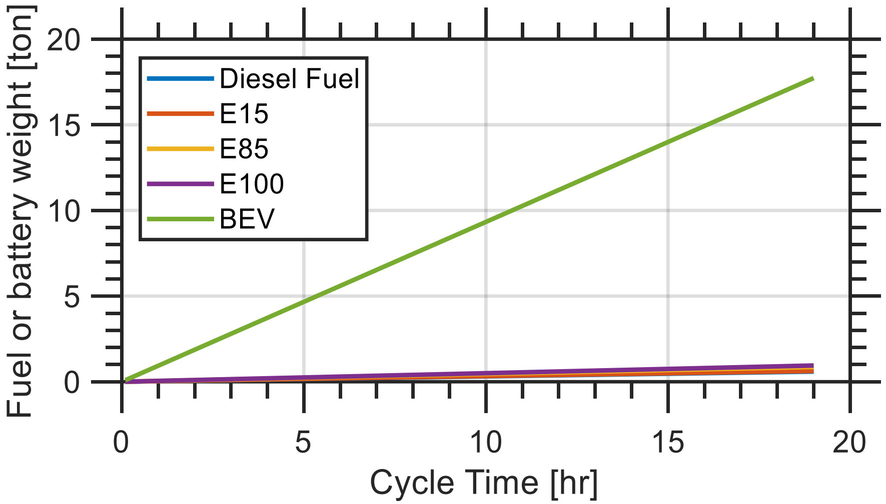
Intake Manifold Temperature

- Due to the large quantity of air moved by the engine, challenging to precisely control the intake temperature
- Undesirable for the combustion process to be sensitive to intake temperature
- Conventional ***diesel*** combustion has very little sensitivity to intake temperature at this operating condition
- ***Gasoline*** & ***Ethanol*** → combustion timing can be sensitive to ***in-cylinder temperature***
  - Intake manifold temperature simply shown as an example
  - Required in-cylinder heat could be obtained from TBC, trapped hot residuals, uncooled EGR, multiple injections, etc.



Simple Analysis of HD Class 8 Truck – Comparison of CO_2 Emissions



- Class 8 Truck and Trailer
-107 kW constant brake power

- 42.5% BTE ICE (Fixed)

- US Avg Grid CO2 = 418 g/kW-hr
- 250 W-hr/kg Battery
- 85% battery charging eff., 90% discharge eff., and 94% electric motor eff.